National Aeronautics and Space Administration

EXPLORESPACE TECH

In Situ Propellant and Consumable Production (ISPCP)

Gerald Sanders – System Capability Leader for In-Situ Resource Utilization

In Situ Propellant & Consumable Production (ISPCP)

Driving Outcomes

LEAD	THRUSTS	OUTCOMES
Ensuring American global leadership in Space Technology • Lunar Exploration building to Mars and new discoveries at extreme locations • Robust national space technology engine to meet national needs • U.S. economic growth for space industry • Expanded commercial enterprise in space	**Go** *Rapid, Safe, & Efficient Space Transportation*	• Enable Human Earth-to-Mars Round Trip mission durations less than 750 days. • Enable rapid, low cost delivery of robotic payloads to Moon, Mars and beyond. • Enable reusable, safe launch and in-space propulsion systems that reduce launch and operational costs/complexity and leverage potential destination based ISRU for propellants.
	Land *Expanded Access to Diverse Surface Destinations*	• Enable Lunar and Mars Global Access with ~20t payloads to support human missions. • Land Payloads within 50 meters accuracy while also avoiding local landing hazards.
	Live *Sustainable Living and Working Farther from Earth*	• Conduct Human/Robotic Lunar Surface Missions in excess of 28 days without resupply. • Conduct Human Mars Missions in excess of 800 days including transit without resupply. • Provide greater than 75% of propellant and water/air consumables from local resources for Lunar and Mars missions. • Enable Surface habitats that utilize local construction resources. • Enable Intelligent robotic systems augmenting operations during crewed and un-crewed mission segments.
	Explore *Transformative Missions and Discoveries*	• Enable new discoveries at the Moon, Mars and other extreme locations. • Enable new architectures that are more rapid, affordable, or capable than previously achievable. • Enable new approaches for in-space servicing, assembly and manufacturing. • Enable next generation space data processing with higher performance computing, communications and navigation in harsh deep space environments.

- **Resource Mapping/Estimation:** Enable global and detailed local and subsurface mapping of lunar resources and terrain, especially for water in permanently shadowed craters, for science, future exploration, and commercial use

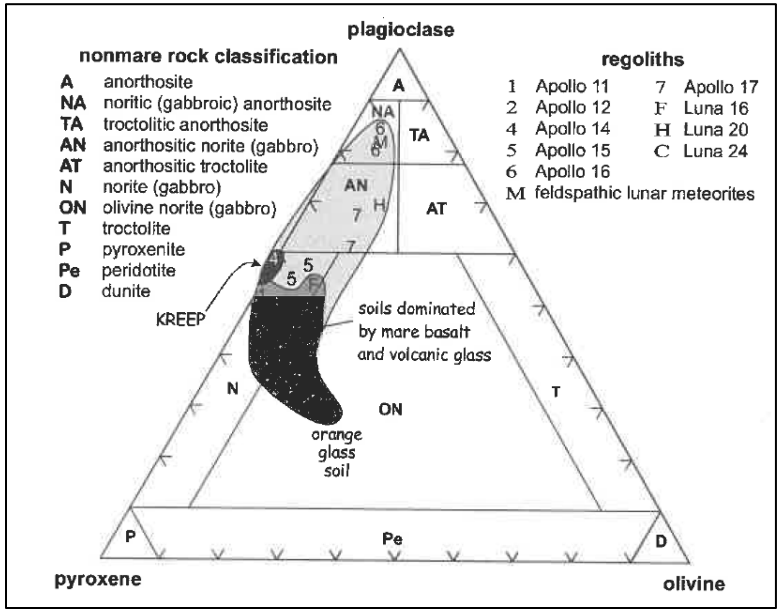
- **Oxygen Extraction:** Enable extraction and production of oxygen from lunar regolith to provide 10's of metric tons per year, for up to 5 years with little human involvement and maintenance, for reusable surface and ascent/descent transportation.

- **Water Mining:** Enable cis-lunar commercial markets through extraction of water resources to provide 100's of metric tons of propellant per year for reusable landers and cis-lunar transportation systems

Lunar Resources

Lunar Regolith

- **>40% Oxygen by mass**
  - Silicate minerals make up over 90% of the Moon
- Regolith
  - Mare: Basalt (plagioclase, pyroxene, olivine)
  - Highland/Polar: >75% anorthite, iron poor
- Pyroclastic Glass
- KREEP (Potassium, Rare Earth Elements, Phosphorous)
- Solar Wind Implanted Volatiles

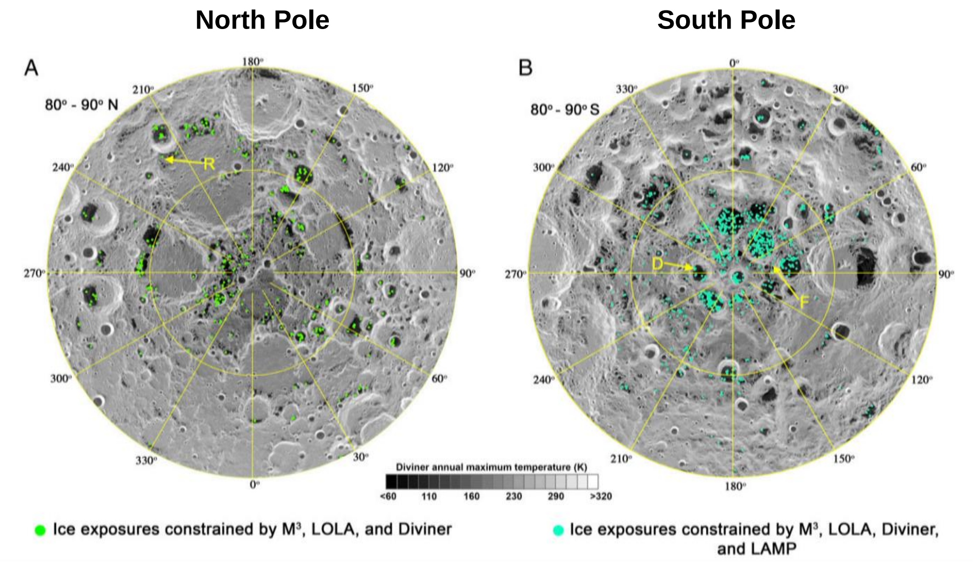


From *New Views of the Moon*

Polar Water/Volatiles

- LCROSS impact estimated **5.5 wt%** water along with other volatiles
- Green and blue dots show positive results for surface water ice and temperatures <110 K using orbital data.
- Spectral modeling shows that some ice-bearing pixels may contain **~30 wt % ice** (mixed with dry regolith)

➢ *Without direct measurements, form, concentration, and distribution of water is unknown*



Li et. al, (2018), *Direct evidence of surface exposed water ice in the lunar polar regions*

	Concentration (%wt)*
H_2O	5.5
CO	0.70
H_2	1.40
H_2S	1.74
Ca	0.20
Hg	0.24
NH_3	0.31
Mg	0.40
SO_2	0.64
C_2H_4	0.27
CO_2	0.32
CH_3OH	0.15
CH_4	0.03
OH	0.00
H_2O (adsorb)	0.001-0.002
Na	

Table courtesy of Tony Colaprete

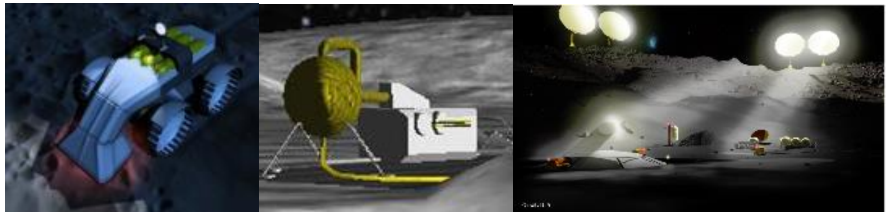
Lunar Surface ISPCP Capabilities
'Prospect to Product'

Resource Assessment – Looking for Water/Minerals

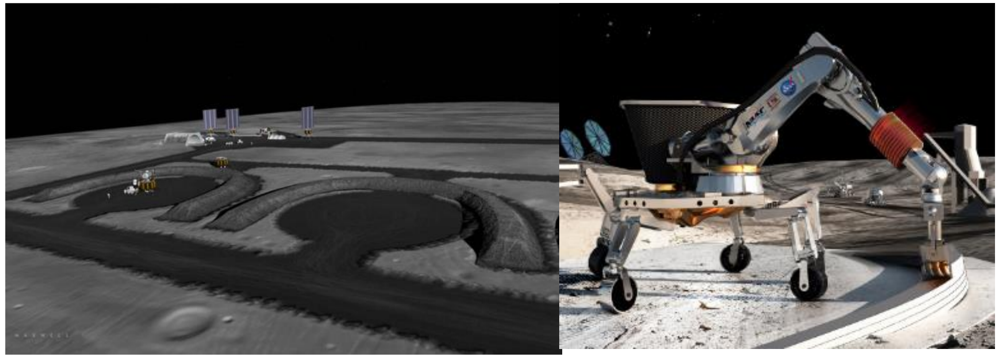
Global Assessment

Local Assessment

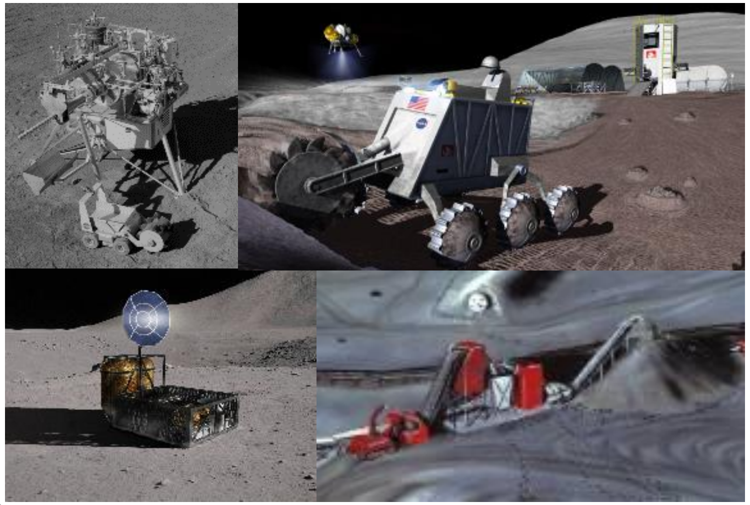
Mining Polar Water & Volatiles



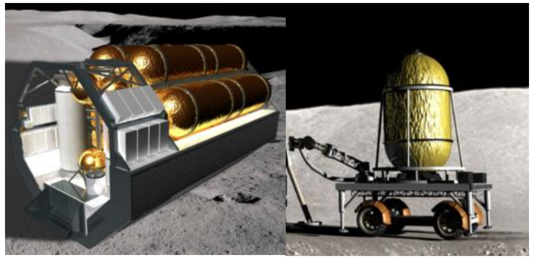
Landing Pads, Berms, Roads, Shielding and Structure Construction (AMSM)



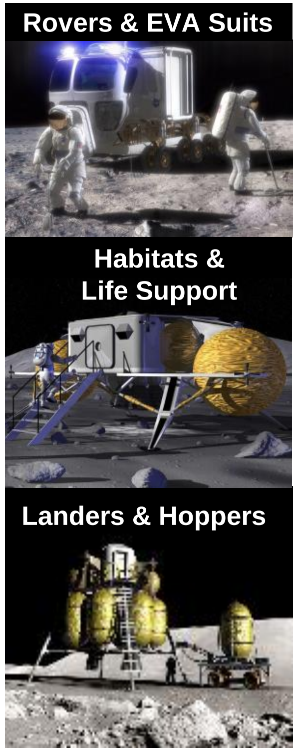
Excavation & Regolith Processing for O_2 & Metal Production



Consumable Storage & Delivery (CFM)



Consumable Users



ISPCP Functional Breakdown

- **All Functions have been mapped to interactions with other STPs**
- **Functions used as starting point for technology and gap assessments**
- **Emphasis placed on Bolded Functions**

Destination Reconnaissance and Resource Assessment

- Site Imaging/Terrain Mapping
- **Instruments for Resource Assessment**
- Orbital Resource Evaluation
- **Local Surface Resource Evaluation**
- **Resource/Terrain/Environment Data Fusion and Analyses**

Resource Acquisition, Isolation, and Preparation

- Resource Excavation & Acquisition
- Resource Preparation before Processing
- Resource Transfer
- Resource Delivery from Mine Site and Removal

Resource Processing for Production of Mission Consumables

- Resource Storage and Feed To/From Processing Reactor
- **Regolith Processing to Extract Oxygen**
- **Regolith Processing to Extract Water**
- Carbon Dioxide Processing
- Water Processing
- Instrumentation to Characterize Processing Performance
- Product/Reactant Separation
- Contaminant Removal from Reagents/Products

Resource Processing for Production of Manufacturing and Construction Feedstock

- In Situ Excavation and Movement for Construction
- Resource Preparation for Construction Feedstock
- Material transfer
- Resource Processing to Extract Metals/Silicon
- Resource-Trash/Waste Gas Processing to Produce Methane/Plastics

Cross Cutting

- Planetary Simulants for Test & Verification
- Planetary Regolith/Environment Test Chambers

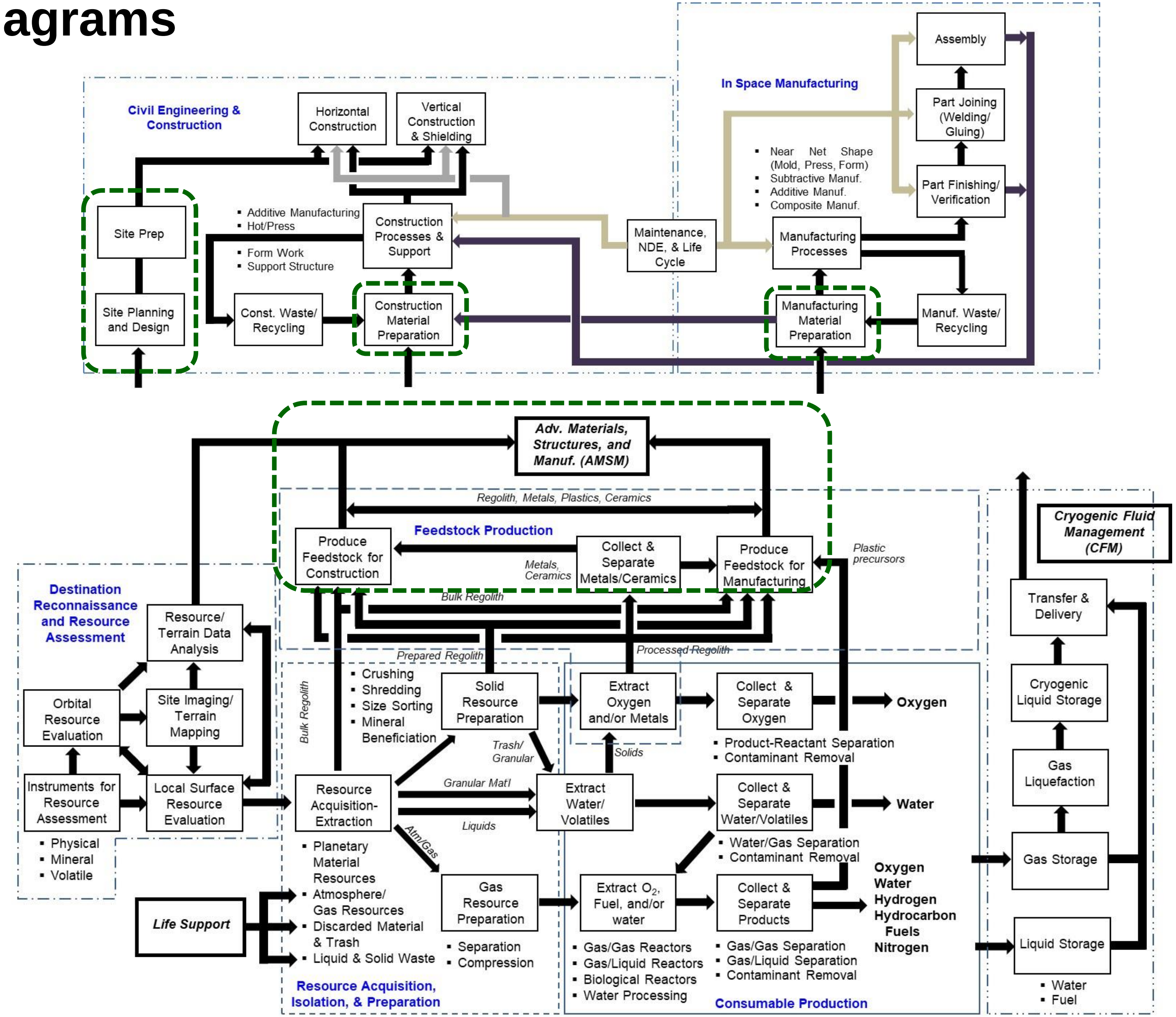
Shared Interest/Responsibilities with Advanced Manufacturing Structures, and Manufacturing (AMSM) STP

- PT Materials and Manufacturing – J. Vickers
- PT Materials, Structures, and Nanotechnology – M. Hilburger

ISRU Functional Block Diagrams

Use to

- Help understand connectivity:
  - Internally
  - With other STPs
  - Cross-cutting w/ AMSM
- Focus assessment of technology options in each sub-function
- Understand influence of technologies on complete system



ISRU Functional And Gap Connectivity to Other STPs

= ISPCP-led Gap Currently Identified

= Other Capability-led Identified

= ISPCP SCDP Gap linked to AMSM Capability Need

\# = Known number of Gaps

WBS #	In Situ Propellant & Consumable Production	**In Situ Prop/Consumables**	Cryogenic Fluid Management	Advanced Life Support & Human Performance	Adv Materials, Structures, and Manufacturing		Advanced Power Systems	Autonomous Sys. & Robotics	Extreme Access/Environment	On-orbit Servicing, Assembly, and Manufacturing	Advanced Avionics	Advanced Communications & Navigation	Small Spacecraft
1.0	**Destination Reconnaissance and Resource Assessment**												
1.1	Site Imaging/Terrain Mapping							2					
1.2	Instruments for Resource Assessment												
	Instruments for Physical/Geotechnical Characterization	1											
	Instruments for Mineral/Chemical Characterization	1											
	Instruments for Volatile Characterization	4											
1.3	Orbital Site and Resource Evaluation	2											6
1.4	Local Surface Resource Evaluation												
	Instrument Integration/operation	1											
	Mobility-Traversibility for Resource Assessment	1						1					
	Remote Ops/Autonomy for Resource Assessment							1					
	Comm&Nav for Resource Assessment							1		4			
	Power in Extreme Environment												
1.5	Resource/Terrain/Environment Data Fusion and Analyses	1											
2.0	**Resource Acquisition, Isolation and Preparation**												
2.1	Resource Excavation/Acquisition												
	Granular	1											
	Hard - mineral and/or icy	1											
	Mars Atmosphere	1											
2.2	Resource Preparation before Processing												
	Size Reduction - Crushing/Grinding	1				1							
	Mineral Seperation	1				1							
	Size Sorting - Fractions	1				1							
	Atmosphere Constituent Separation	3											
.2.3	Resource Transfer												
	Solid Material Transfer	2											
	Gas Transfer												
2.4	Resource delivery from Mine Site and Removal												
	Implement integration/operation	1											
	Mobility-Traversibility for Resource Delivery/Removal	1						2					
	Autonomy for Resource Delivery/Removal							2		3			
	Comm&Nav for Resource Delivery/Removal									6			
	Power for Resource Delivery/Removal												

WBS #	In Situ Propellant & Consumable Production	**In Situ Prop/Consumables**	Cryogenic Fluid Management	Advanced Life Support & Human Performance	Adv Materials, Structures, and Manufacturing		Advanced Power Systems	Autonomous Sys. & Robotics	Extreme Access/Environment	On-orbit Servicing, Assembly, and Manufacturing	Advanced Avionics	Advanced Communications & Navigation	Small Spacecraft
3.0	**Resource Processing for Production of Mission Consumables**												
3.1	Resource Storage and Feed To/From Processing Reactor	1											
3.2	Regolith Processing to Extract Oxygen	2											
3.3	Regolith Processing to Extract Water												
	Enclosed reactor	2											
	Subsurface heating/vapor collection	2											
3.4	Carbon Dioxide Processing												
	Carbon Dioxide to Oxygen	2											
	Carbon Dioxide to Methane	2											
3.5	Water Processing	2		3									
3.6	Instrumentation to Characterize Processing Performance												
	Instruments for mineral/chemical characterization	1											
	Instruments for product purity characterization	1											
3.7	Product/Reactant Separation	2		1									
3.8	Contaminant Removal from Reagents/Products	1		3									
3.9	Power for Resource Processing												
	Solar thermal	1											
	Electrical						3						
3.10	Autonomous/Supervised Processing Operations	1						2					
3.11	Surface Cryogenic Product Liquefaction, Storage & Transfer												
	O_2/CH_4 Liquefaction		1										
	H_2 Liquefaction		1										
	O_2/CH_4 Zero-loss Storage		1										
	H_2 Zero-loss Storage		1										
	O_2/CH_4 Zero-loss Transfer		1							1			
	H_2 Zero-loss Transfer		1							1			
4.0	**Resource Processing for Production of Manufacturing and Construction Feedstock**												
4.1	In Situ Excavation and Movement for Construction	5											
4.2	Resource Preparation for Construction Feedstock												
	Shape/Size Manipulation	1											
	Constituent Manipulation	1											
	Feedstock Quality Measurement	1											
4.3	Material transfer	2											
4.4	Resource Processing to Extract Metals/Silicon	2											
4.5	Trash/Waste Processing												
	To Plastic	2		2									

In Situ Propellant & Consumable Production (ISPCP)
Phases of Evolution and Use

	Demo Scale	Pilot Plant	Crewed Ascent Vehicle*	Full Descent Stage*	Single Stage to NRHO**	Human Mars Transportation[t]	Commercial Cis-Lunar Transportation[^]
			3 Stage Arch to NRHO				
Timeframe	days to months	6 mo - 1 year	1 mission/yr	1 mission/yr	1 mission/yr	per year	per year
Demo/System Mass[^^]	10's kg to low 100's kg	1 mt O_2 Pilot 1.3 – 2.5 mt Ice Mining	1400 to 2200 kg	2400 to 3700 kg	Not Defined	Not Defined	29,000 to 41,000 kg
Amount O_2	10's kg	1000 kg	4,000 to 6,000 kg	8,000 to 10,000 kg	30,000 to 50,000 kg	185,000 to 267,000 kg	400,000 to 2,175,000 kg
Amount H_2	10's gms to kilograms	125 kg		1,400 to 1,900 kg	5,500 to 9,100 kg	23,000 to 33,000 kg	50,000 to 275,000 kg
Power for O_2 in NPS	100's W	~3 KW	20 to 32 KW	40 to 55 KW	N/A	N/A	N/A
Power for H_2O in PSR	100's W	~2 KW		~25 KW	14 to 23 KW		150 to 800 KW
Power for H_2O to O_2/H_2 in NPS		~4 KW		~48 KWe	55 to 100 KWe		370 to 2,000 KWe

NPs = Near Permanent Sunlight

PSR = Permanently Shadowed Region

*Estimates from rocket equation and mission assumptions

**Estimates from J. Elliott, "ISRU in Support of an Architecture for a Self-Sustained Lunar Base "

[t] Estimate from C. Jones, "Cis-Lunar Reusable In-Space Transportation Architecture for the Evolvable Mars Campaign"

[^] Estimate from "Commercial Lunar Propellant Architecture" study

[^^] Electrical power generation and product storage mass not included

- Table use best available studies and commercial considerations to guide development requirements/FOMs
- Table provides rough guide to developers and other surface elements/Strategic Technology Plans for interfacing with ISRU

Lunar ISRU Strategy: Leader/Follower

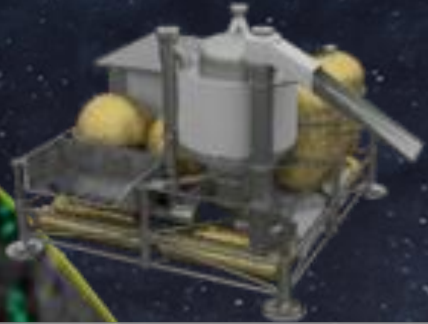
STMD has a **leader/follower** path defined for lunar ISRU

- Ice mining (Leader) – Potential to provide LO_2/LH_2 propulsion, crew consumables, and water for radiation protection
- O_2 from regolith (follower) – Provide oxidizer and crew consumables

Precursors and demonstrations

- Volatile prospecting with PRIME-1 & VIPER (2022)
- O_2 from Regolith high-fidelity ground demo in TVC in FY20 – 22/23

Knowledge gained from precursors and demonstrations will inform the decision for Pilot and Full-scale Plants



Pilot Plant

- Relevant scale plant (100's of kg/yr)
- Demonstrates core capabilities and subsystems
- Products available for SMD, HEOMD, or commercial partners

ISRU Lunar Development and Demonstration Timeline

Reconnaissance, Prospecting, Sampling | **Resource Acquisition & Processing** | **Pilot Consumable Production**

Sub-system Demonstrations: Investigate, sample, and analyze the environment for mining and utilization.

Follow The Natural Resources: Demonstrations of systems for extraction and processing of raw materials for future mission consumables production and storage.

Sustainable Exploration: Scalable Pilot - Systems demonstrating production of consumables from in-situ resources in order to better support sustained human presence.

CLPS Drill Down Select

High-fidelity Simulant Production

Oxygen from Lunar Simulant Ground Demos

Polar Resources Ice Mining Experiment (Prime-1) on CLPS

Volatiles Investigation Polar Exploration Rover (VIPER)

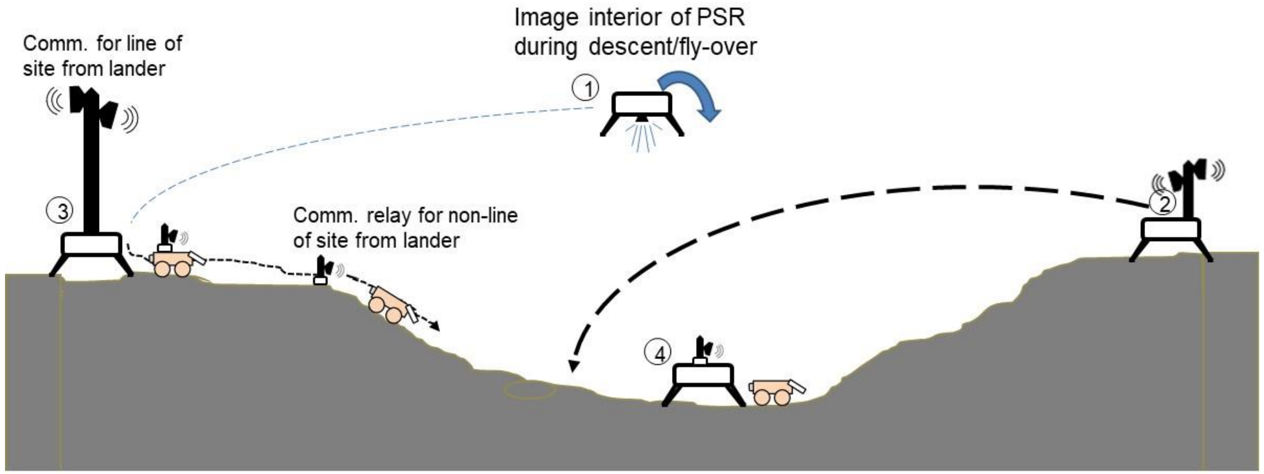
ISRU Subsystem Consumables Extraction Demos

Scalable Pilot - ISRU Systems for Consumable Production

2019 → 203x

ISRU Concepts of Operation – Water Resource Assessment

Exploratory Evaluation of Polar Resources

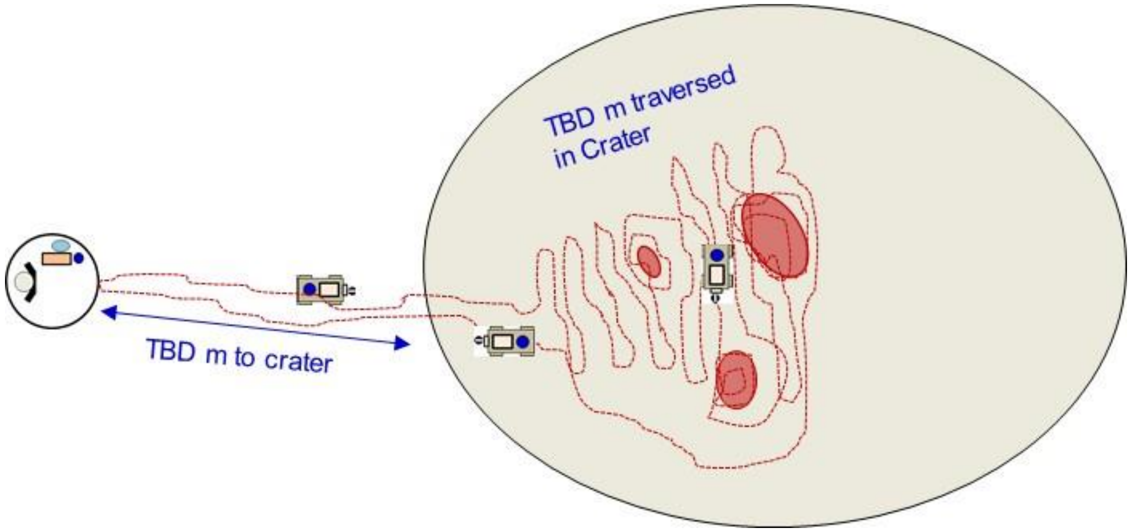


1. Ejectable/deployable payloads into PSR during descent/fly-over: Payloads are short-lived stationary or mobile assets
2. Ejectable/deployable payloads into PSR after landing near PSR: Payloads are short-lived stationary or mobile assets
3. Payloads deployed after landing next to PSR. Communication from orbit, lander, or relay deployed at PSR rim.
4. Land directly in PSR. Communication from lander. Payload is attached to lander or deployable for short duration operation

Landing Options
- In PSR
- On edge/rim of PSR

Power Options
- Batteries
- Power Beaming
- Power Cables

Detailed-Focused Polar Resource Assessment



Landing Options
- In PSR or in shadowed crater
- On edge/rim of PSR

Power Options
- Nuclear reactor, batteries on rover
- Advanced RTG on rover with batteries
- Solar arrays in sunlight, batteries on rover
- Solar arrays in sunlight, fuel cell on rover

Communication & Navigation Options for Rover
- Orbital relay to Earth via Gateway or communication satellite
- Line of site or Non-line of site communication relays from rover-to-lander, with lander-to-Earth direct or thru relay

Note: Need near continuous communications to allow for tele-operation

ISRU Concepts of Operation - Ice Mining

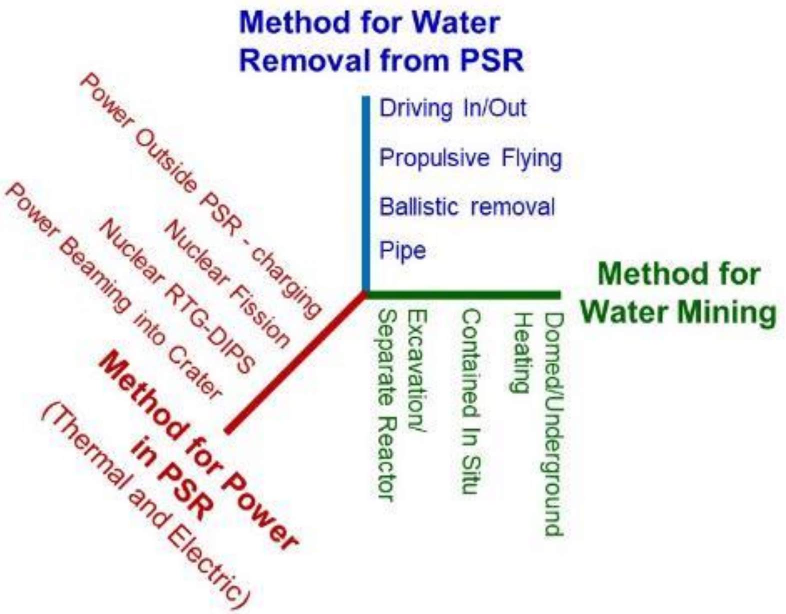
Currently Low TRL and Significant Resource Unknowns

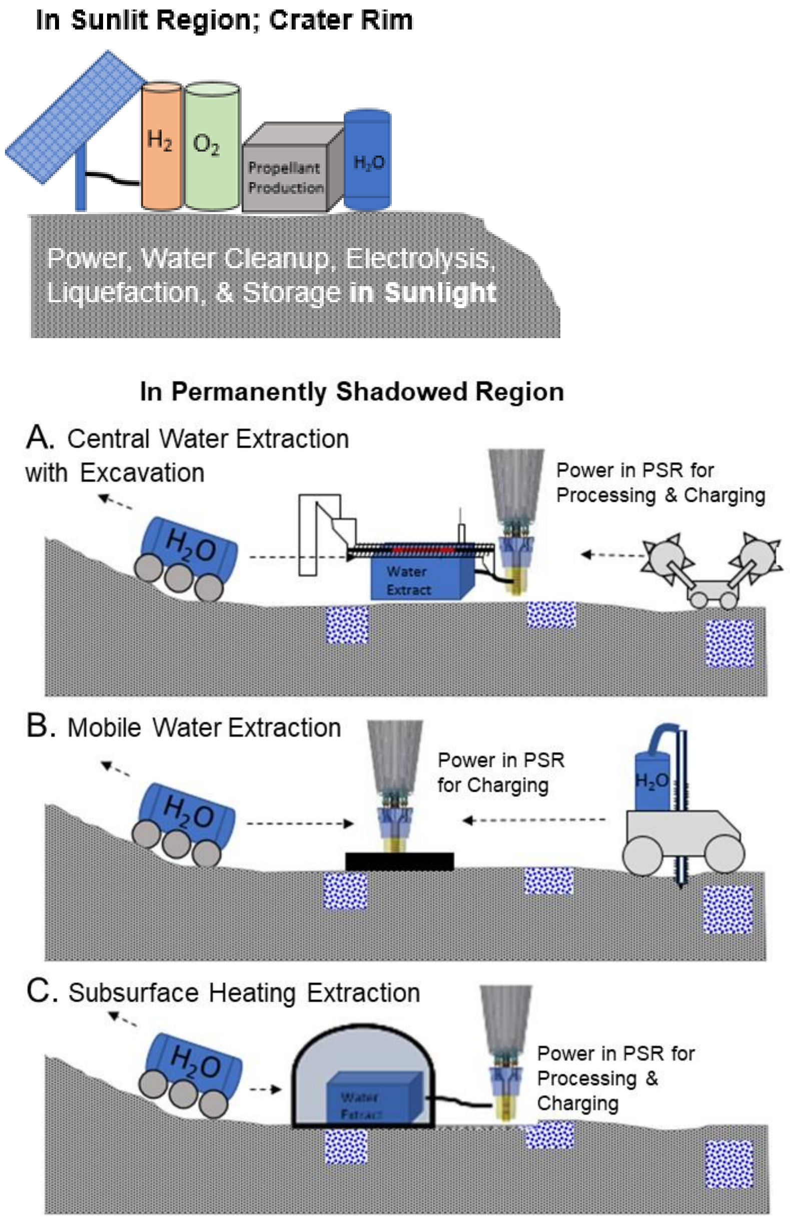
- **Three main drivers for Water Mining Architecture viability**
  1. Method of Water Mining
  2. Method of Power in Crater
  3. Method of Water removal from Crater

- **Application of *Mining Technologies* are highly dependent on:**
  - **Resource Depth Access**: How deep the water resource can be for a given concept to work.
  - **Spatial Resource Definition:** How homogenous is the resource
  - **Resource Geotechnical Properties**: How hard and porous is the icy regolith
  - **Volatiles Retention:** How much of the volatiles are captured vs lost to the environment.
  - **Material Handling:** How much interaction is required with the regolith.

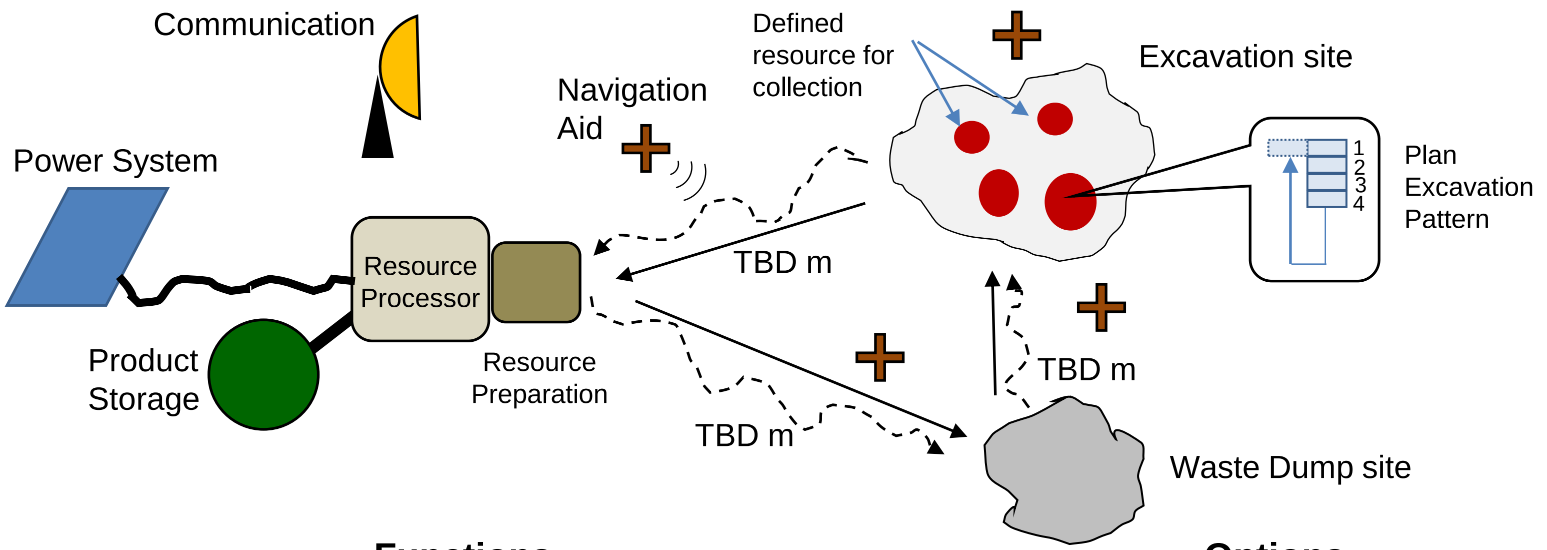
Preliminary Assessment

Concepts	Architecture Option			Status	Resource Depth access	Spatial Resource definition	Volatiles retention	Material Handling
	IRSU plant	Mobile	In-situ					
Auger Dryer	X			Breadboard Laboratory hardware	Moderate (cm)	10s of Meters	Low-moderate	High
Microwave Vessel	X	?		Breadboard Laboratory hardware	Moderate (cm)	10s of Meters	Low-moderate	High
Microwave Zamboni		X	X	Concept Study	Surface	10s of Meters	Low	Low
Vibrating Tray	X	X		Breadboard Laboratory hardware	Moderate (cm)	10s of Meters	Low-moderate	High
Coring Auger		X	X	Breadboard Laboratory hardware	Deep (m)	Meters	High	Moderate
Heated Dome			X	Concept Study	Surface	Meter	High	Low
Heated batch (Resolve EBU)	X	?		Field demonstrations	Moderate (cm)	10s of Meters	Low-moderate	High
Water jet/Dome			X	Concept Study	Moderate (cm)	Meter	High	Low

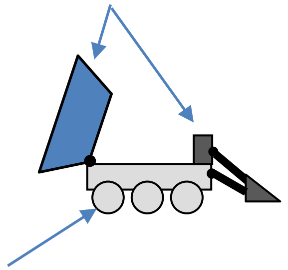




ISRU Concepts of Operation – Oxygen (Metal) Extraction
TRL 2 to 5 Depending on the Process/Technology



Implements
– Removable / Exchangeable
– Common structure, data, electrical interface



High Traction Mobility Platform
- Removable/ Exchangeable Parts
- Common motors/parts with Implements

= Unprepared path
= Prepared path
TBD = 100 to 1000 m

- **Central Control** – Commands multiple assets
- **Smart Platforms** – Each is aware of what the others are doing

Functions	Options
Traverse back and forth from desired endpoints: plant, resource zone, dump zone	• Smart control and sensors on rover: it selects its own path and avoids obstacles • Path selected on Earth, rover follows path: internal nav or external beacons
Rover selects location for drilling/excavation	• Patterns / locations selected on Earth • Location determined as rover arrives based on past knowledge and site survey • Rover goes to location: internal nav, external beacons, and/or imaging/LIDAR
Device interacts with soil/regolith	• Operate extraction device depending on material: drill, auger, downhole scoop, bucket-wheel/drum, ripper, etc • Pre-planned motions, force-feedback autonomous, human controlled.
Rover interacts with ISRU Plant	• Locates and delivers soil/regolith for processing; Locates and receives spent regolith • Locates dirty water transfer connection for On-rover soil processing • Locates and connects to charging port for battery or fuel cell resupply
ISRU Plant processes regolith	• Pre-established operating conditions and timelines • Regolith pre/post evaluation for process efficiency evaluation and adjustment

ISPCP Capability Gaps

Resource Assessment Capability Gaps

- Surface features and geotechnical data on regolith outside and inside permanently shadowed craters (PSRs)
- Understanding of water and contaminants as a function of depth and areal distribution
- Understanding of subsurface water/volatile release with heating
- Resolution of hydrogen and subsurface ice at <10's m scale (or less) for economic assessment & mine planning (orbital/surface)
- Instrument for polar regolith sample heating and released volatile characterization (minimum loss during transfer/evaluation)
- Long duration operations at <100 K temperatures and lunar vacuum
- Traversibility inside and in/out of PSRs
- Increased autonomy and better communications into PSRs
- Long-duration mobile polar resource assessment operations (nuclear or power beaming)

Mining Polar Water Capability Gaps

- Limited knowledge/understanding of polar water depth, distribution, concentration to at least 1 m below the surface and multiple sq km.
- Limited knowledge/understanding of regolith properties within PSR
- Feasibility and operation of downhole ice/water vaporization and collection in cold-trap under lunar PSR conditions
- Feasibility and operation icy regolith transfer and processing in reactor under lunar PSR conditions
- Other volatile capture and separation; contaminant removal
- Water electrolysis, clean-up, and quality measurement for subsequent electrolysis or drinking (10,000's kg)
- Long-term operation under lunar PSR environmental conditions (100's of days, 10,000's kg of water)
- Electrical power & Thermal energy in PSRs for ice mining/processing (10's of KWs)

Oxygen Extraction Capability Gaps

- Increase scale of regolith processing by 1 to 3 orders to reach minimum of 10 mT O_2/yr (depending on method)
- Increase duration operation under lunar environmental conditions (100's of days, 10,000's kg of O_2)
- Long-life, regolith transfer (100's mT) and low leakage regolith inlet/outlet valves (10,000's cycles)
- Deployable large scale solar collection/thermal energy transfer for regolith melting
- Regenerative oxygen clean-up for direct oxygen production (10,000's kg)
- Water electrolysis, clean-up, and quality measurement for subsequent electrolysis or drinking (10,000's kg)
- Autonomous process monitoring, including measuring mineral properties/oxygen content before and after processing

SBIRs are Important to Fill ISRU Gaps

Recent Solicitation Topics and Selections

SBIR 2020

Solar concentrators for O2/Construction
- Solar Concentrator Oxygen Reactor with Continuous Heating - Blueshift

Lunar Ice Mining
- Thermal Management System for Ice Miners – Advanced Cooling Technologies
- ISRU Collector of Ice in the Cold Lunar Environment – Paragon Space Development
- Lunar Ice Mining Using a Heat-Assisted Cutting Tool – Sierra Lobo

Novel O2 Extraction
- Ionic Liquid-Assisted Electrochemical Extraction of Oxygen – Faraday Technology
- Molten Regolith Electrolysis – Lunar Resources

SBIR 2019

Solar concentrators for O2/Construction
- Deployable Solar Concentrator - Opterus Research
- Solar Concentrator for Lunar Applications – Physical Sciences*

Molten Oxide Electrolysis

Beneficiation/Size Sorting
- Size Sorted Regolith Systems – Grainflow Dynamics
- Payloads for Lunar Resources: Volatiles
- Lunar Exploration Gas Spectrometer – Pioneer Astronautics
- NeuRover – Radiation Detection Technologies*

SBIR 2018

Mars Atmosphere Collection and Separation
- Liquid Sorption Pump – Pioneer Astronautics*
- Gas Inlet Sensor for Measuring Dust Particle Size – Southwest Sciences

Carbon Dioxide Processing
- Room Temperature Electrolysis for O2 Generation – Dioxide Materials
- Redox Tolerant Cathode for SOE Stacks – OxEon*
- Highly Efficient Separation and Recirculation of Unreacted CO2 – TDA Research
- Dehydration Resistant and Dimensionally Stable High Performance Membrane – Giner
- Humidity Monitor for ISRU on Mars – Intelligent Optical Systems

Lunar Resources: Volatiles - Small Payloads for Lunar Mission
- High Resolution Scanning of Sub-Surface Liquid Water with Mobile Neutron Spectrometer – Radiation Detection Technologies

**= Phase II award*

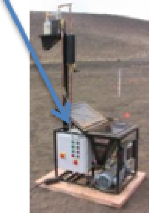
Success Story: Infusion of Multiple SBIR Derived Subsystems Into In-Situ Resource Utilization (ISRU) Analog Field Test

2009 Phase III – Carbothermal Reduction of Regolith, Orbital Technologies Corp., to be completed 9/30/2010
2001 & 2002 Phase I's – Carbothermal Reduction of Regolith, Orbital Technologies Corp., completed 4/30/2002, 7/30/2003
2006 & 2009 Phase II & III – Solar Concentrator, Physical Sciences Inc., completed 4/21/2009 (III) & to be 09/29/2010 (II)
2009 Phase II & IPP – Pneumatic Regolith Transport, Honeybee Robotics, Phase II completed 5/30/2009, IPP on 2/26/2010
2007 Phase II & III– LO_2/CH_4 Thruster, WASK, completed 2009

Dust to Thrust – End-to-end processing and use of lunar derived oxygen

Constellation Application:

CxP Need: Oxygen Production from Lunar Regolith & Surface Construction of Landing Pads
Vehicle Elements: Lunar Surface Systems Outpost
ETDP Project: In-Situ Resource Utilization (ISRU) Project

LO_2/CH_4 Thruster	Pneumatic Regolith Transport	Carbothermal System	Solar Concentrator
			
• 17 test fires, with reliable ignition despite dusty field environment • Operated on oxygen produced from regolith	• 0.6 – 0.7 kg per minute transfer; 99% material removal from pneumatic gas	• 9.5 to 10% oxygen extraction efficiency; complete regeneration of methane reactant; water collected for processing	• Up to 1750 C to tephra surface and 54 to 60% efficiency even with non-optimum primary mirrors and fiber optics (to reduce cost)